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Life cycle assessment of second generation ethanol derived from banana agricultural waste: Environmental impacts and energy balance

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ABSTRACT

Biofuels are considered as an alternative to partially replace fossil fuels and mitigate climate change effects. A life cycle assessment of second generation ethanol, derived from banana agricultural wastes, was developed to assess its environmental sustainability and demonstrate its capacity of reducing greenhouse gas emissions. The methodological approach was conducted in a Well-to-Wheel perspective, using as functional unit 1 MJ of energy released in the combustion of bioethanol in a passenger car from different bioethanol blends. Primary and secondary information sources were used for the assessment; mass balance and ethanol yield data came from laboratory experimentation. The environmental assessment was carried out using SimaPro 8.0.4.30 with the ReCiPe midpoint (H) impact assessment methodology. The quantified impact categories were climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), photochemical oxidant formation (PO), particulate matter formation (PM), and fossil depletion (FD). In addition, net energy value and energy ratio (ER) were analyzed to ensure a positive energy balance. Compared to using pure gasoline, blended gasoline reduced CC, PO, PM, and FD impacts, but increased FE and TA impacts. The obtained energy balance was positive, with an ER of 2.68 MJ/MJ. Wastewater treatment is the process that presented the greatest energy consumption. Since Ecuador is the world's largest exporter of bananas, and a great amount of agricultural waste is available, a case study in this country was analyzed. This case study indicated that Ecuador could use banana residue for ethanol production, considering its positive and negative impacts. In conclusion, second generation ethanol derived from banana agricultural waste has potential to reduce greenhouse gas emissions and fossil depletion and has a positive energy balance.

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1. Introduction

Environmental sustainability is a concept that has gained a lot of attention during the last decade due concerns about intensive fossil fuel use and its possible effects on climate change. In 2016, the United Nations released the 2030 Agenda for Sustainable Development, which aims to guide and stimulate actions over the next fifteen years in areas of critical importance for humanity and the planet (United Nations, 2016). The Agenda places a goal of substantially increasing the amount of global energy production from renewable sources by 2030 to seriously address climate change and its impacts. In short, increasing energy production from renewable sources, considering climate change criteria, must become a milestone for every country.

Globally, transportation uses the largest share of final energy (Ballesteros, 2010). Of total global energy demand, 40% is consumed in the form of liquid fuels (Nanda et al., 2015). Electric vehicles are expected to represent a quarter of cars on the road by 2040, displacing 13 million barrels (2067 million liters) per day of crude oil (BNEF, 2016), but this change will take time, money, and political will, and until that happens some efforts must focus on short-term solutions. Biofuels can be part of the solution. Indeed, bioethanol can be used in low blends with gasoline without engine modification. Among all the biofuels available in the market, bioethanol is the predominant alternative, and it has been successfully integrated into the national fuel systems of some countries in low blends with regular gasoline (Handler et al., 2016).

In order to ensure raw material diversification for ethanol production, and to avoid the dependence on staple crops, such as

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sugarcane, corn, and wheat, second generation (2G) ethanol technologies draw on lignocellulosic biomasses, such as forest and agricultural residues, energy crops, etc. In most developing countries, agriculture is a primary source of gross domestic product, and this activity produces large amounts of waste, which has little to no revalorization in productive activities. Consequently, concerns about sustainability and security of fossil fuel use, along with advances in biomass conversion technology, have stimulated the interest in crop residue use as bioenergy feedstocks (Cherubini and Ulgiati, 2010).

Ecuador is an upper middle-income country that bases its economy on oil extraction and agricultural activities (The World Bank, 2016). Since 2015, Ecuador has been in a transition process to change its energy mix, including liquid fuels. With Executive Order 675, the government aims to achieve full replacement of regular gasoline with blended gasoline (termed *ecopaís*) to a maximum of E10 (a 10% anhydrous ethanol and 90% regular gasoline fuel mixture) throughout the country, depending on the ethanol availability and production. According to this mandate, nationwide E5 (5% ethanol and 95% gasoline) distribution should be achieved by 2017, followed by full E10 in 2018, but this target is a challenge because ethanol production in 2015, based entirely on sugarcane, only accounted for 25% of national demand (Ministerio de Producción, 2016). Given this deficit and the necessity to diversify ethanol production, new local feedstocks must be studied in order to determine the ethanol production potential of each material.

Banana is a perennial tropical crop, from the *Musaceae* family, which generates a bunch of fruit once in its life. In addition, it is the most important fruit crop in the world, in terms of harvested metric tons. In 2014, banana production reached 114 million tons, with 26% of production concentrated in Latin America (FAO, 2017). Among nations, Ecuador is the largest global exporter, covering approximately 30% of worldwide exports (Pro Ecuador, 2015).

Banana crop management produces a large amount of agricultural waste, which could be employed in bioethanol production. According to Guerrero et al. (2016), the El Oro Province is one of the three most productive banana provinces in Ecuador and has the potential for bioenergy production. This crop generates two types of waste: (i) starchy (from all fruits failing to achieve commercial standards) and (ii) lignocellulosic (from pseudostems and leaves, normally found on the field, and rachis of the fruit bunches usually gathered in packing plants). In this article, only rachis is considered, with the intention of analyzing the environmental impact of second generation ethanol produced from this raw material.

To ensure sustainability of second generation biofuels, it is necessary to confirm that the energy produced from lignocellulosic biomass is greater than the energy consumed in its production (Ojeda et al., 2011). Life cycle assessment (LCA) allows the numerical measurement of environmental sustainability and provides more information than offered by an environmental footprint assessment. Several LCAs have been performed to identify the environmental performance of waste management and residual biomass transport (Muñoz et al., 2015), used for the production of biochar (Muñoz et al., 2017), as well as for bioethanol production from different lignocellulosic feedstocks and its subsequent use in diverse type of blends (Møller et al., 2014; Weinberg and Kaltschmitt, 2013). Most of these studies showed a clear reduction in greenhouse gas (GHG) emissions, but there are some differences in other impact categories. The differences could be attributed to the type of raw material studied. For example, a dedicated energy crop requires more inputs than a residue. Moreover, each biomass requires different transformation processes, depending strictly on its chemical composition. Indeed, the ethanol yield and mass balance also depend on it.

To the best of our knowledge, no LCA study has been conducted to assess the environmental impacts of bioethanol from lignocellulosic banana waste. This study aims to provide information on the environmental impacts of the use of different gasoline blends using second generation ethanol derived from banana agricultural waste, in order to ensure its environmental sustainability. It may also serve as an information source for policy makers, banana producers, and the scientific community related to the development of 2G bioethanol to determine if it is an eco-friendly fuel.

2. Materials and methods

This study analyzes the environmental performance of gasoline blended with second generation ethanol obtained from banana rachis, along its life cycle considering residue collection, transformation, and energy performance. The functional unit, defined as the quantified performance of a system for its use as reference unit (ISO, 2006a), was 1 MJ of energy released by combustion in a passenger car, in agreement with the principles of the Well-to-Wheels (WtW) approach (Cavalett et al., 2013; Rocha et al., 2014).

2.1. System boundaries

The studied system is a combination of several technologies that are jointly applied for the production of cellulosic bioethanol and its blending with regular gasoline. The system boundaries were considered using a WtW approach (see Fig. 1), where impacts were evaluated considering the extraction of raw materials (from the well), its transformation, distribution, and final use (to the "wheels") (Morales et al., 2015). This type of system boundary is commonly used in life cycle assessment of liquid fuels (Orsi et al., 2016; Patil et al., 2016).

The assessment focused on the environmental performance of second generation ethanol from banana rachis, so more detailed information will be provided about its productive process. The impact of gasoline, which was assumed would be blended with bioethanol at the refinery, was considered a system process. Guerrero et al. (2016) established potential emplacement of transformation plants by bioenergy means, employing banana waste as raw material. This information was used to determine the travel distances in this study.

Bioethanol production requires some physical and chemical processes to break down the plant cell wall, where the carbohydrates of interest (cellulose and hemicellulose) are located (see Table 1). Collected rachis would be transported 20 km to a transformation plant. In the production stage, milling reduced particle size to at least 10 mm. The milled biomass was then overnight soaked with diluted H_2SO_4 (1.5% v/v). Afterwards, the material was exposed to a hydrothermal pretreatment known as steam explosion at 198 °C for 5 min (Guerrero et al., 2017). Next, the material went to a decanter where the solid and liquid fractions were separated. The solid fraction then went into the fermentation tank, where enzymes were added for the 8-h pre-saccharification stage. Then, *Saccharomyces cerevisiae* was added to ferment the sugars available in the liquid fraction for 64 h. Once saccharification and fermentation were finished, the slurry went to the distillation column where 99.5% ethanol was recovered, using combinations of distillation and molecular sieves (Aden et al., 2002).

The solid residue obtained after the distillation could be revalorized because it contained residual cellulose, hemicellulose, and lignin as major component (see Table 1). In consequence, this residue has a high lower heating value (20.2 MJ/kg) and could be used for steam and electricity production by combustion in a fluidized bed reactor (Aden et al., 2002). Similarly, the burning of lignin

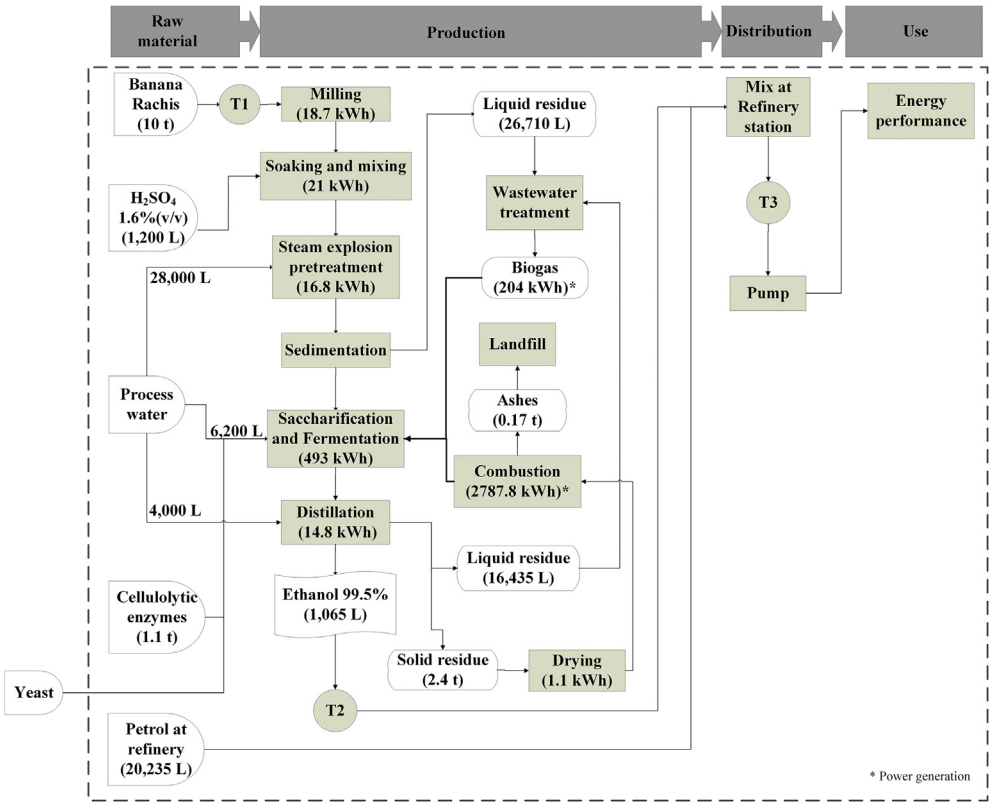

Fig. 1. Life cycle system of second generation ethanol production from rachis of banana bunch.

Table 1
Chemical composition of banana rachis, and lignin residue obtained after fermentation. Data presented as percentage of total dry matter (g/100 g).

	Rachis	Lignin residue
Starch	3.1 ± 0.2	–
Cellulose	23.0 ± 1.1	9.5 ± 0.3
Hemicellulose	11.2 ± 2.2	1.9 ± 0.1
Lignin	10.8 ± 0.5	70.2 ± 0.9
Ash	29.9 ± 0.9	13.5 ± 0.0
Extractives	18.2 ± 0.5	–
Acetyl groups	0.7 ± 0.2	–
Total	96.9 ± 1.1	95.2 ± 0.3

residue, obtained in a production process of bioethanol from tall fescue grass, was found sufficient to meet the steam requirement in second generation ethanol production process (Kumar, 2014).

In the distribution stage, ethanol would be sent 185 km from the transformation plant to the refinery for blending; gasoline data were taken from the Ecoinvent v.3 database. Following blending, E5 gasoline would be distributed to the pumps (25 km on average) and sold to consumers. Finally, energy performance was studied considering a typical passenger car.

2.2. Inventory and key assumptions

The optimization of the production process and mass balances were determined through experimental tests conducted at the Research Centre for Energy, Environment and Technology - CIEMAT (Madrid, Spain), getting primary information to build the life cycle inventory. In addition, secondary information, such as databases, scientific literature, and equipment operational manuals, were used to simulate the scaling process to industrial level, considering that the transformation plant will require 10 t of rachis in dry matter basis to produce 1065 L of anhydrous ethanol, daily. It is important to highlight that rachis has a 70 kg/t residue-to-product ratio on a fresh matter basis. Table 2 summarizes the life cycle inventory data used in the assessment of the second generation ethanol production process.

In order to identify the environmental aspects associated with E5 gasoline, the Ecoinvent v.3 database, from the SimaPro 8.0.4.30 library, was used. While Ecuador's electricity mix is not available in this database, it was developed using national data: hydro (43.2%), diesel (27.8%), natural gas (17.6%), oil (8%), biomass (2.5%), solar (0.5%), and wind (0.4%) (ARCONEL, 2016).

Transport distance was analyzed according to data from Guerrero et al. (2016). Three transport stages were considered: T1) transport of the biomass from the field to the transformation plant located in El Oro Province (20 km) using a transport truck >20 t, considering an empty return trip. T2) Transport of ethanol from the transformation plant to the Pascuales storage terminal, located in Guayas Province (185 km), using a small lorry transport of 7.5 t total mass. T3) Transport from the Pascuales storage terminal to the fuel pump, using an average distance of 25 km. This final distance was obtained analyzing the location of a random selection of 10% of the total fuel pumps in Guayas Province. In this step, a freight lorry of 3.5–7.5 metric tons was considered.

The following assumptions were made:

- Details of minor equipment, such as valves and pumps, were not included in this model (Kumar and Murthy, 2011).
- The impact of yeast production was not included because of the lack of information (Bosco et al., 2011).
- The solid residue obtained at the end of the distillation, which is mainly composed of lignin, a structural polymer that cannot be

Table 2
Global inventory for E5 gasoline blended with second generation ethanol derived from banana rachis.

Inputs from the technosphere			
Materials	Value	Energy	Value (kWh)
Banana rachis [b]	10.0 t	Electric power from Ecuador's national grid	769.4
Sulfuric acid ETH (1.6%) LCA Food DK	12.0 t	Lignin residue combustion	2787.8
Process water, ion exchange, production mix, at plant, from surface water	38.2 t	Methane combustion	204.0
Cellulolytic enzymes	1.1 t	**Types of Transport** [a]	**Value (tkm)**
Gasoline (regular),	20,235 L	Transport,	100
from crude oil, at refinery		truck >20 t	
		Small lorry transport 7.5 t	185
		Transport, freight, lorry 3.5–7.5 t	400

Outputs to the technosphere	
Materials	Value
Ethanol (99.5%)	1065 L
Lignin residue[b]	2.4 t
Methane	137.9 m^3

[a] In all cases an empty return was considered.
[b] In dry matter basis.

fermented and contains a high lower heating value, can be harnessed as solid fuel for power generation, necessary at various stages of the process. Since burning lignin residue does not meet the energy plant's demand, considering a 21% power conversion efficiency (Guerrero et al., 2016), some energy comes from the national grid.

- It was assumed that wastewater would be treated with anaerobic and aerobic digestion to reach the water quality characteristics required by Ecuadorian environmental law (known by its Spanish acronym "TULAS") (Presidencia de la República del Ecuador, 2003). Biochemical oxygen demand (BOD_5) was measured using the OxiTop® measuring system, and showed 2520 mg/L. Chemical oxygen demand (COD) was measured using the dichromate reflux method, and showed 9656 mg/L. Considering these characteristics, the studied wastewater treatment was an Upflow Anaerobic Sludge Blanket (UASB) that had a COD removal efficiency of 95%, with a biogas yield of 290 L/kg of removed COD, which contains 70% methane in its composition (Enitan et al., 2015). The produced methane was considered to be burned for power generation with a gas turbine, considering a 28% electricity efficiency (Bove and Lunghi, 2006).
- Finally, ashes from the lignin residue combustion, which are inorganic and not reactive, were assumed that be landfilled.

2.3. Allocation methodology

Allocation is required for multi-output processes, and the selection of an allocation approach for processes that produce more than one co-product can have a large impact on the results (Karlsson et al., 2014). In this study, no environmental burdens were assigned to banana rachis, because it was considered that wastes are not attributed as input and output flows of the product system. In fact, a mass allocation exercise was carried out showing that rachis represents 0.93% of the environmental burdens of banana production (Iriarte et al., 2014), considering it negligible. Moreover, ISO 14044 requires clear definitions of cut-off criteria for including inputs and outputs, as well as the assumptions that establish those criteria (ISO, 2006b). The cut-off criterion has been used in relation to environmental relevance, indicating that processes contributing less than 1% of the environmental impact are outside the system limits. In addition, since agricultural residue conversion into bioethanol can be credited for avoiding the waste treatment chain (Wiloso et al., 2012), all the environmental burdens for producing this residue were assigned to the main product, banana fruit.

According to the fundamentals of clean development mechanisms, co-products, by-products, and wastes are defined according to their economic value. Co-products produce similar revenues as the main product; by-products have a much lower value than co-products; and wastes have zero or negative value (Singh et al., 2010). Using this specification, lignin residue was allocated as a co-product in terms of energy (Karlsson et al., 2014), due to its capacity to be used as solid biofuel, which could be reinjected to the system to reduce the plant energy demand. In addition, all the methane produced in the wastewater treatment stage was also allocated as a co-product for use in power generation.

2.4. Impact assessment

The life cycle impact assessment was based on the local situation and used to evaluate the quantity and significance of potential environmental impacts from a defined system throughout its entire life cycle (ISO, 2006a, 2006b).

The 2G bioethanol production process was modeled in SimaPro 8.0.4.30, (PRé Consultants, Amersfoort, the Netherlands). ReCiPe midpoint (hierarchist version) was used for the impact assessment, and the total cumulative energy demand (CED) methodology, version 1.09, was used for the energy analysis.

The following impact categories were included in the analysis, which include the default categories required by the international EPD® system (EPD, 2016): Climate Change (CC, kg CO_2 eq), Terrestrial Acidification (TA, kg SO_2 eq), Freshwater Eutrophication (FE, kg P eq), Photochemical Oxidant Formation (PO, kg NMVOC), Particulate Matter Formation (PM, kg PM10 eq), and Fossil Depletion (FD, kg oil eq). Special attention has been paid on CC, FD, and energy balance to ensure bioethanol's environmental sustainability.

The results were analyzed in three different scenarios:

1. The production and use of second generation bioethanol without gasoline blending, in order to detect the production processes or hotspots that could be improved.
2. Current and future Ecuador-specific scenarios, using full gasoline, the 2017 blending target, and the 2018 blending target. These scenarios include an uncertainty analysis as described in Muñoz et al. (2016). The uncertainty analysis represents the errors produced by measurement variability, lack of data, assumptions, database variability, and the various sources of information. Uncertainty for each inventory datum was calculated using the Pedigree Matrix (Supplementary Material), which generates a log-normal distribution for each characterized impact category. Then, the uncertainty analysis was performed using a Monte Carlo simulation (1000 runs), with a 95% confidence interval using SimaPro.

3. A sensitivity analysis was developed considering different percentages of ethanol blends with regular gasoline to study how the blending percentage could influence environmental profiles, and comparing these results with full gasoline and full ethanol, in order to discuss a tentative optimal blend.

3. Results and discussion

LCA results strongly depend on the information quality used as input. Given this issue, when LCA is applied to provide quantitative assessments, data quality is of high relevance. In this study, mass balance data were obtained from laboratory experimentation. The pretreatment stage can be found in Guerrero et al. (2017), and the saccharification and fermentation stage results can be found in Guerrero et al. (2018).

3.1. Scenario 1: production and use of second generation bioethanol

The LCA results of the impact categories selected in this study, for the production and use of 1 MJ of second generation bioethanol are shown (Table 3.)

Since the main purpose of bioethanol production is decreasing GHG emissions, this study indicates that 2G bioethanol produced from banana rachis emits less GHG than regular gasoline, considering a WtW approach. In the CC impact category, the use of 1 MJ of bioethanol emits 0.031 kg CO_2 eq, compared to 0.088 kg CO_2 eq (Ecoinvent database, v.3) or 0.072 kg CO_2 eq (EPA, 2014) for 1 MJ of regular gasoline.

The CC impact calculated in this study is similar to that from assessments developed with different agricultural wastes and different conversion technologies (Morales et al., 2015). For example, Woods and Bauen (2003) determined that production of second generation ethanol from wheat straw could vary from 0.023 to 0.072 kg CO_2 eq/MJ, depending on the technology. Meanwhile, a study of the same material using sulfuric acid catalyzed steam explosion as pretreatment found that the climate change category has an impact of 0.084 kg CO_2 eq/MJ (Wang et al., 2013), which is higher than other studies. Finally, Handler et al. (2016) quantified the global warming potential of carbon containing feedstocks, like forest residues (0.015 kg CO_2 eq/MJ) and corn stover (0.036 kg CO_2 eq/MJ). There are methodological differences between these studies; the most notable are the electricity provided by different energy mixes, industrial practices, facility size, and inventory data.

In this study, each stage of the analyzed process affects each impact category differently (Fig. 2). The most relevant process is wastewater treatment, which has a high presence in five of the six studied categories (Wang et al., 2013). Indeed, it makes up almost the entire FE impact and 52.3% of TA. These high impacts could be mainly attributed to the large water volumes required for biomass transformation; the use of sulfuric acid in the biomass pretreatment; the high COD and BOD_5 produced by the extractive removal from the biomass (e.g., volatile oils, terpenes, fatty acids and their esters, waxes, polyhydric alcohols, alkaloids, and aromatic compounds); and the high energy demand of the anaerobic and aerobic treatments (See Fig. 3).

Table 3
Potential environmental impacts derived from the well-to-wheels LCA of 1 MJ of second generation bioethanol.

Impact category	Unit/UF	Total
Climate change	kg CO_2 eq	0.0315
Terrestrial acidification	kg SO_2 eq	0.0001
Freshwater eutrophication	kg P eq	$1.0 \cdot 10^{-05}$
Photochemical oxidant formation	kg NMVOC	0.0001
Particulate matter formation	kg PM_{10} eq	$5.0 \cdot 10^{-05}$
Fossil depletion	kg oil eq	0.0066

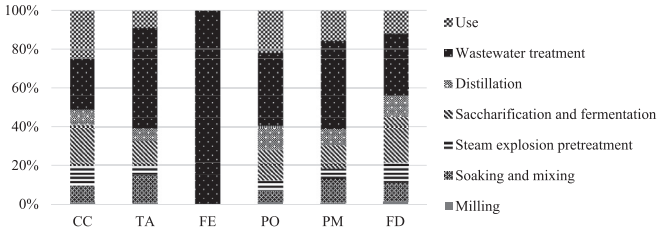

Fig. 2. Contribution of each process involved in the production of second generation bioethanol to the impact categories studied.

Regarding the energy balance, 2G bioethanol production was characterized in terms of Net Energy Value (NEV), defined as the energy required to produce 1 L of bioethanol minus the energy content of ethanol (Velásquez-Arredondo et al., 2010); and Energy Ratio (ER), defined as the energy output of the system and the energy input needed to operate it. Negative NEV or an ER less than one indicates that the energy used to produce the biofuel was greater than that of the energy content of the fuel (Kumar and Murthy, 2012).

Fig. 3 presents the energy requirements for each process, and shows a NEV of 7.88 MJ/L. This result is within the reported range of NEV of cellulosic bioethanol production, which is between 1.5 MJ/L (Luo et al., 2009) to 18.9 MJ/L (Cardona and Sánchez, 2006). In addition, the ER is 2.68 MJ/MJ. Higher values of ER indicate higher energy efficiency, and it is possible that energy improves with internal energy re-use (Baeyens et al., 2015), so this efficiency could be attributed to the significant input of energy from the solid lignin residue obtained after fermentation as well as power generation from biogas produced during wastewater treatment. The positive energy balance of this second generation bioethanol demonstrates that it has the capacity to displace fossil fuels.

3.2. Scenario 2: current and future scenarios of Ecuador

Since this study was developed using parameters specific to Ecuador, it can be used to compare scenarios using its gasoline blending mandates, of E5 gasoline (ecopaís) in 2017, E10 in 2018 and the use of full gasoline (G100). These scenarios help understand the environmental impacts in Ecuador associated with using second generation ethanol derived from banana agricultural waste.

Blending bioethanol with gasoline can improve CC, PO, PM, and FD (Fig. 4). The reductions in CC and PM are due to the capacity of ethanol to enhance complete combustion, because it contains 35% oxygen, which reduces the particulate matter and GHG emissions (Nanda et al., 2015). In the case of FD, the reduction is proportional

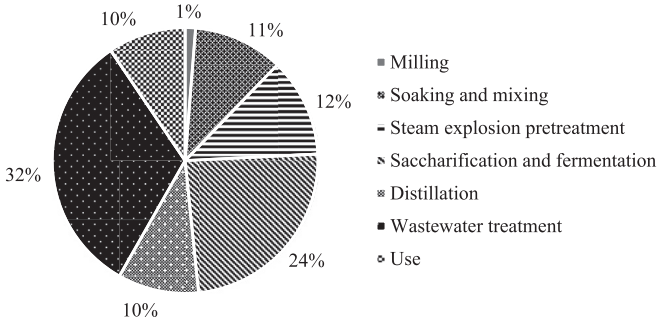

Fig. 3. Energy requirements of second generation bioethanol processes.

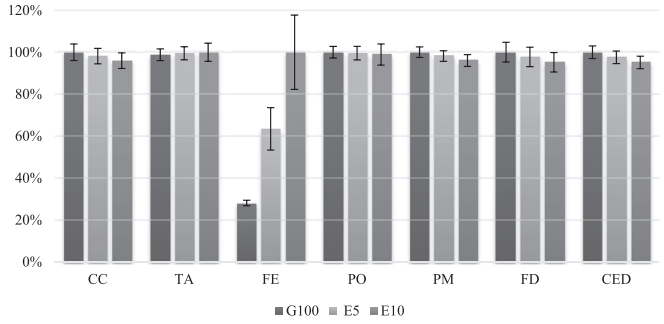

Fig. 4. Environmental impact of different blends of ethanol and regular gasoline in Ecuador.

to the volume displaced by the biofuel. Although few significant differences exist in the evaluated impact categories when compared to 100% gasoline, there is a greater probability of lowered CC, PM, and FD impacts when regular gasoline is blended with banana-rachis bioethanol (Fig. 5). Moreover, the CED decreases as the percentage of ethanol increases, which is another fact that contributes to the improvement of CC impacts (Fig. 4).

FE and TA show higher probabilities of increased impacts with increasing ethanol blends, because of the high water use in ethanol production, and the input of organic matter in the effluent. In fact, there was a 100% probability of higher impacts in the use of blended gasoline on FE impacts (Fig. 5). This effect is highly dependent on the amount of ethanol, because the impact of gasoline on these categories is negligible (see Fig. 6).

The uncertainty analysis (Supplementary Material) shows that there is low variability in data from the selected impact categories, because most inventory data were obtained from laboratory measures, geographical information system sources from the area of study and collected in the previous three years. This ensures that the data quality and the results can be used for academic purposes or as a pool of information for decision makers. In addition, the uncertainty analysis demonstrates that there are higher probabilities to have lower impacts on climate change. Moreover, Fig. 4 shows an impact reduction trend, and Fig. 5 (uncertainty analysis) demonstrates that there are higher probabilities to have lower impacts on climate change, particulate matter formation, and fossil depletion categories when regular gasoline is blended with ethanol from banana rachis.

Given this, the Ecuadorian government must analyze the use of 2G bioethanol in its blending mandates, considering its own environmental targets. This study demonstrates the feasibility of using 2G bioethanol, which likely has a smaller water footprint than the first-generation bioethanol (Chiu et al., 2015) currently used in ecopaís gasoline. As such, the results of the current study encourage the development of a comparable WtW LCA analysis of the current ecopaís fuel blend in order to determine the more sustainable bioethanol fuel blend.

3.3. Scenario 3: sensitivity analysis

The sensitivity analysis results show that ethanol-based fuels can offer improved environmental performance in impact categories such as climate change, as well as a decrease in energy resources based on fossil fuels (Fig. 6). However, the use of gasoline could be the best option in terms of other impact categories, such as terrestrial acidification, and water related categories (González-García et al., 2012). Morales et al. (2015) also reported this behavior, showing that a greater blend of 2G bioethanol in gasoline reduces GHG emissions, but affects negatively freshwater eutrophication and water depletion categories.

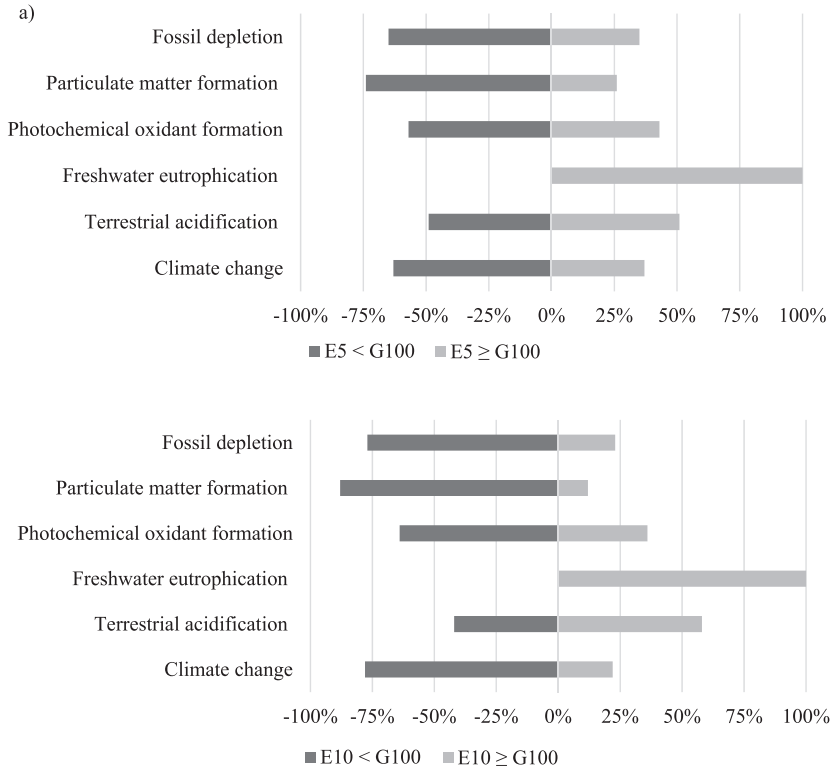

Fig. 5. Uncertainty evaluation using Monte Carlo analysis with a 95% confidence interval of the proposed scenarios. Comparing a) E5 vs. G100 and b) E10 vs. G100.

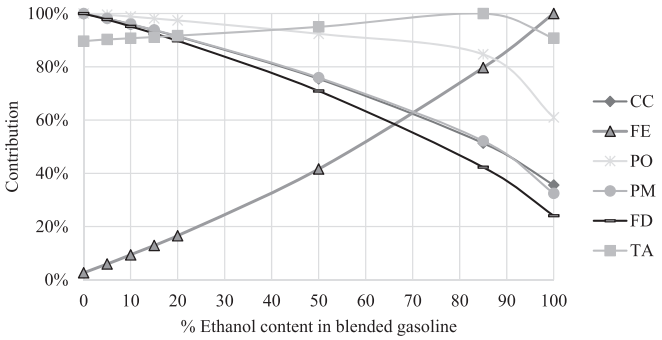

Fig. 6. Sensitivity analysis for different blends of gasoline with ethanol.

Comparing second generation ethanol from banana wastes with regular gasoline, three categories showed improvements (PM, FD, and CC). Moreover, the full replacement of gasoline with ethanol in transportation avoids fossil depletion by 80%. Finally, the blend where improvements and negative impacts cross is 65%, which implies the use of a flex-fuel vehicle.

4. Conclusions

The second generation ethanol from banana lignocellulosic wastes has potential to reduce GHG emissions and fossil depletion and has a positive energy balance. Due to its greatest energy consumption, the wastewater treatment should be improved in order to enhance the performance of the second generation ethanol productive chain.

Biofuels should not be judged in a generic way, since they have tradeoffs that must be considered according to the site and country contexts. As demonstrated, bioethanol improves some environmental impact categories and aggravates others. Considering this, a tentative optimal blend in the Ecuadorian context of the study was established at 65% ethanol. However, achieving this blend requires across-the-board improvements in passenger car engines.

Once this article focused on studying the environmental impacts, is advisable more information about the economic and social aspects to ensure the sustainability of second generation bioethanol derived from banana agricultural waste.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.10.298.

References

Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., Montague, L., Slayton, A., Lukas, J., 2002. Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover [WWW Document]. NREL Tech. Rep. http://www.nrel.gov/docs/fy02osti/32438.pdf. (Accessed 16 June 2016).

ARCONEL, 2016. National Electric Power Balance (in Spanish) [WWW Document]. http://www.regulacionelectrica.gob.ec/estadistica-del-sector-electrico/balance-nacional/. (Accessed 21 June 2016).

Baeyens, J., Kang, Q., Appels, L., Dewil, R., Lv, Y., Tan, T., 2015. Challenges and opportunities in improving the production of bio-ethanol. Prog. Energy Combust. Sci. 47, 60–88. https://doi.org/10.1016/j.pecs.2014.10.003.

Ballesteros, M., 2010. Introduction to biofuels (in Spanish). In: Sebastián, F., García-Galindo, D., Rezeau, A. (Eds.), Energía de La Biomasa. Prensas Universitarias de Zaragoza, Zaragoza, pp. 395–415.

BNEF, 2016. Electric Vehicles to Be 35% of Global New Car Sales by 2040 [WWW Document]. http://about.bnef.com/press-releases/electric-vehicles-to-be-35-of-global-new-car-sales-by-2040/. (Accessed 21 June 2016).

Bosco, S., Di Bene, C., Galli, M., Remorini, D., Massai, R., Bonari, E., 2011. Greenhouse gas emissions in the agricultural phase of wine production in the Maremma rural district in Tuscany, Italy. Ital. J. Agron. 6, 93–100. https://doi.org/10.4081/ija.2011.e15.

Bove, R., Lunghi, P., 2006. Electric power generation from landfill gas using traditional and innovative technologies. Energy Convers. Manag. 47, 1391–1401. https://doi.org/10.1016/j.enconman.2005.08.017.

Cardona, C., Sánchez, O., 2006. Energy consumption analysis of integrated flowsheets for production of fuel ethanol from lignocellulosic biomass. Energy 31, 2447–2459. https://doi.org/10.1016/j.energy.2005.10.020.

Cavalett, O., Chagas, M.F., Seabra, J., Bonomi, A., 2013. Comparative LCA of ethanol versus gasoline in Brazil using different LCIA methods. Int. J. Life Cycle Assess. 18, 647–658. https://doi.org/10.1007/s11367-012-0465-0.

Cherubini, F., Ulgiati, S., 2010. Crop residues as raw materials for biorefinery systems – a LCA case study. Appl. Energy 87, 47–57. https://doi.org/10.1016/j.apenergy.2009.08.024.

Chiu, C.C., Shiang, W.-J., Lin, C.J., Wang, C.-H., Chang, D.-M., 2015. Water footprint analysis of second-generation bioethanol in Taiwan. J. Clean. Prod. 101, 271–277. https://doi.org/10.1016/j.jclepro.2015.03.068.

Pro Ecuador, 2015. Banana and Plantain (in Spanish) [WWW Document]. http://www.proecuador.gob.ec/compradores/oferta-exportable/banano/. (Accessed 15 June 2016).

Enitan, A.M., Adeyemo, J., Swalaha, F.M., 2015. Anaerobic digestion model to enhance treatment of brewery wastewater for biogas production using UASB reactor. Environ. Model. Assess. https://doi.org/10.1007/s10666-015-9457-3.

EPA, 2014. Greenhouse Gas Equivalencies Calculator [WWW Document]. https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator. (Accessed 25 May 2016).

EPD, 2016. Characterisation Factors for Default Impact Assessment Categories [WWW Document]. http://environdec.com/en/The-International-EPD-System/General-Programme-Instructions/Characterisation-factors-for-default-impact-assessment-categories/. (Accessed 27 February 2017).

FAO, 2017. FAOSTAT [WWW Document]. http://www.fao.org/faostat/en/#data/QC. (Accessed 31 January 2017).

González-García, S., Luo, L., Moreira, M.T., Feijoo, G., Huppes, G., 2012. Life cycle assessment of hemp hurds use in second generation ethanol production. Biomass Bioenergy 36, 268–279. https://doi.org/10.1016/j.biombioe.2011.10.041.

Guerrero, A.B., Aguado, P.L., Sánchez, J., Curt, M.D., 2016. Gis-based assessment of banana residual biomass potential for ethanol production and power generation: a case study. Waste Biomass Valorization 7, 405–415. https://doi.org/10.1007/s12649-015-9455-3.

Guerrero, A.B., Ballesteros, I., Ballesteros, M., 2017. Optimal conditions of acid-catalysed steam explosion pretreatment of banana lignocellulosic biomass for fermentable sugar production. J. Chem. Technol. Biotechnol. https://doi.org/10.1002/jctb.5239.

Guerrero, A.B., Ballesteros, I., Ballesteros, M., 2018. The potential of agricultural banana waste for bioethanol production. Fuel 213C, 176–185.

Handler, R.M., Shonnard, D.R., Griffing, E.M., Lai, A., Palou-Rivera, I., 2016. Life cycle assessments of ethanol production via gas fermentation: anticipated greenhouse gas emissions for cellulosic and waste gas feedstocks. Ind. Eng. Chem. Res. 55, 3253–3261. https://doi.org/10.1021/acs.iecr.5b03215.

Iriarte, A., Almeida, M.G., Villalobos, P., 2014. Carbon footprint of premium quality export bananas: case study in Ecuador, the world's largest exporter. Sci. Total Environ. 472, 1082–1088. https://doi.org/10.1016/j.scitotenv.2013.11.072.

ISO, 2006a. ISO 14040-Environmental Management – Life Cycle Assessment – Principles and Framework [WWW Document]. http://www.iso.org/iso/catalogue_detail?csnumber=37456. (Accessed 1 September 2016).

ISO, 2006b. ISO 14044-Environmental Management – Life Cycle Assessment – Requirements and Guidelines [WWW Document]. http://www.iso.org/iso/catalogue_detail?csnumber=38498. (Accessed 1 September 2016).

Karlsson, H., Börjesson, P., Hansson, P.-A., Ahlgren, S., 2014. Ethanol production in biorefineries using lignocellulosic feedstock – GHG performance, energy balance and implications of life cycle calculation methodology. J. Clean. Prod. 83, 420–427. https://doi.org/10.1016/j.jclepro.2014.07.029.

Kumar, D., 2014. Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Experimental, Enzymatic Hydrolysis Modeling, Techno-economic and Life Cycle Assessment Studies. Oregon State University.

Kumar, D., Murthy, G.S., 2011. Impact of pretreatment and downstream processing technologies on economics and energy in cellulosic ethanol production. Biotechnol. Biofuels 4, 1–19. https://doi.org/10.1186/1754-6834-4-27.

Kumar, D., Murthy, G.S., 2012. Life cycle assessment of energy and GHG emissions during ethanol production from grass straws using various pretreatment processes. Int. J. Life Cycle Assess. 17, 388–401. https://doi.org/10.1007/s11367-011-0376-5.

Luo, L., van der Voet, E., Huppes, G., 2009. An energy analysis of ethanol from

cellulosic feedstock—Corn stover. Renew. Sustain. Energy Rev. 13, 2003–2011. https://doi.org/10.1016/j.rser.2009.01.016.
Møller, F., Slentø, E., Frederiksen, P., 2014. Integrated well-to-wheel assessment of biofuels combining energy and emission LCA and welfare economic Cost Benefit Analysis. Biomass Bioenergy 60, 41–49. https://doi.org/10.1016/j.biombioe.2013.11.001.
Morales, M., Quintero, J., Conejeros, R., Aroca, G., 2015. Life cycle assessment of lignocellulosic bioethanol: environmental impacts and energy balance. Renew. Sustain. Energy Rev. 42, 1349–1361. https://doi.org/10.1016/j.rser.2014.10.097.
Muñoz, E., Vargas, S., Navia, R., 2015. Environmental and economic analysis of residual woody biomass transport for energetic use in Chile. Int. J. Life Cycle Assess. 20, 1033–1043. https://doi.org/10.1007/s11367-015-0891-x.
Muñoz, E., Navia, R., Zaror, C., Alfaro, M., 2016. Ammonia emissions from livestock production in Chile: an inventory and uncertainty analysis. J. Soil Sci. Plant Nutr. 16, 60–75. https://doi.org/10.4067/S0718-95162016005000005.
Muñoz, E., Curaqueo, G., Cea, M., Vera, L., Navia, R., 2017. Environmental hotspots in the life cycle of a biochar-soil system. J. Clean. Prod. 158, 1–7. https://doi.org/10.1016/j.jclepro.2017.04.163.
Nanda, S., Azargohar, R., Dalai, A.K., Kozinski, J.A., 2015. An assessment on the sustainability of lignocellulosic biomass for biorefining. Renew. Sustain. Energy Rev. 50, 925–941. https://doi.org/10.1016/j.rser.2015.05.058.
United Nations, 2016. Sustainable Development Knowledge Platform [WWW Document]. https://sustainabledevelopment.un.org/post2015/transformingourworld. (Accessed 15 June 2016).
Ojeda, K., Sánchez, E., Kafarov, V., 2011. Sustainable ethanol production from lignocellulosic biomass – application of exergy analysis. Energy 36, 2119–2128. https://doi.org/10.1016/j.energy.2010.08.017.
Orsi, F., Muratori, M., Rocco, M., Colombo, E., Rizzoni, G., 2016. A multi-dimensional well-to-wheels analysis of passenger vehicles in different regions: primary energy consumption, CO_2 emissions, and economic cost. Appl. Energy 169, 197–209. https://doi.org/10.1016/j.apenergy.2016.02.039.
Patil, V., Shastry, V., Himabindu, M., Ravikrishna, R.V., 2016. Life-cycle analysis of energy and greenhouse gas emissions of automotive fuels in India: Part 2 – well-to-wheels analysis. Energy 96, 699–712. https://doi.org/10.1016/j.energy.2015.11.076.
Presidencia de la República del Ecuador, 2003. Unified Text of Secondary Environmental Legislation. Book VI. Appendix 1. in Spanish) [WWW Document]. http://www.agua.gob.ec/wp-content/uploads/downloads/2012/07/TEXTO_UNIFICADO_LEGISLACION_SECUNDARIA_i.pdf. (Accessed 12 June 2016).
Ministerio de Producción, 2016. Ecopaís Project Report (in Spanish) [WWW Document]. http://www.produccion.gob.ec/wp-content/uploads/2016/03/INFORME-PROYECTO-ECOPA%26Iacute;S-01-03-16-1.pdf. (Accessed 21 October 2016).
Rocha, M.H., Capaz, R.S., Lora, E.E.S., Nogueira, L.A.H., Leme, M.M.V., Renó, M.L.G., Olmo, O.A., 2014. Life cycle assessment (LCA) for biofuels in Brazilian conditions: a meta-analysis. Renew. Sustain. Energy Rev. 37, 435–459. https://doi.org/10.1016/j.rser.2014.05.036.
Singh, A., Pant, D., Korres, N.E., Nizami, A.-S., Prasad, S., Murphy, J.D., 2010. Key issues in life cycle assessment of ethanol production from lignocellulosic biomass: challenges and perspectives. Bioresour. Technol. 101, 5003–5012. https://doi.org/10.1016/j.biortech.2009.11.062.
The World Bank, 2016. Ecuador [WWW Document]. http://datos.bancomundial.org/pais/ecuador. (Accessed 15 June 2016).
Velásquez-Arredondo, H.I., Ruiz-Colorado, A.A., De oliveira junior, S., 2010. Ethanol production process from banana fruit and its lignocellulosic residues: Energy analysis. Energy 35, 3081–3087. https://doi.org/10.1016/j.energy.2010.03.052.
Wang, L., Littlewood, J., Murphy, R.J., 2013. Environmental sustainability of bioethanol production from wheat straw in the UK. Renew. Sustain. Energy Rev. 28, 715–725. https://doi.org/10.1016/j.rser.2013.08.031.
Weinberg, J., Kaltschmitt, M., 2013. Life cycle assessment of mobility options using wood based fuels—comparison of selected environmental effects and costs. Bioresour. Technol. 150, 420–428. https://doi.org/10.1016/j.biortech.2013.08.093.
Wiloso, E.I., Heijungs, R., de Snoo, G.R., 2012. LCA of second generation bioethanol: a review and some issues to be resolved for good LCA practice. Renew. Sustain. Energy Rev. 16, 5295–5308. https://doi.org/10.1016/j.rser.2012.04.035.
Woods, J., Bauen, A., 2003. Technology Status Review and Carbon Abatement Potential of Renewable Transport Fuels in the UK [WWW Document]. http://www.fcrn.org.uk/sites/default/files/DTI_Technology_status_review.pdf. (Accessed 20 July 2016).